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Neutron-Induced Failures in Semiconductor Devices

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WPI Seminar

May 7, 2014

Outline

- **Introduction to single event effects**

- **Environmental neutron flux**

- **System response**

- **Los Alamos Neutron Science Center (LANSCE) neutron testing facility**

- **Examples of SEE measurements**

- **Issues for testing, conclusion and summary**

Recent avionics incident highlight Single Event Effects (SEE) problem

- On October 7, 2008 , Quantas 72 was enroute from Singapore to Perth, Australia

- "While ..at 37,000 ft, **one of the aircraft's three Air Data Inertial Reference Units (ADIRU) started outputting intermittent, incorrect values**…Two minutes later …the aircraft flight control primary computers **commanded the aircraft to pitch down**. … **At least 110 of the 303 passengers and nine of the 12 crew members were injured**: 12 of the occupants were seriously injured and another 39 received hospital medical treatment." (Pg. vii)

- "The other potential **triggering event was a single event effect (SEE)** resulting from a high-energy atmospheric particle striking one of the integrated circuits within the CPU module. There was insufficient evidence available to determine if an SEE was involved, but **the investigation identified SEE as an ongoing risk for airborne equipment**." (pg. xvii)

- "Testing was conducted with neutrons at 14 MeV …the test was not sufficient to examine the …. susceptibility to the full range of neutrons at the higher energy levels that exist in the atmosphere". (pg. 147)
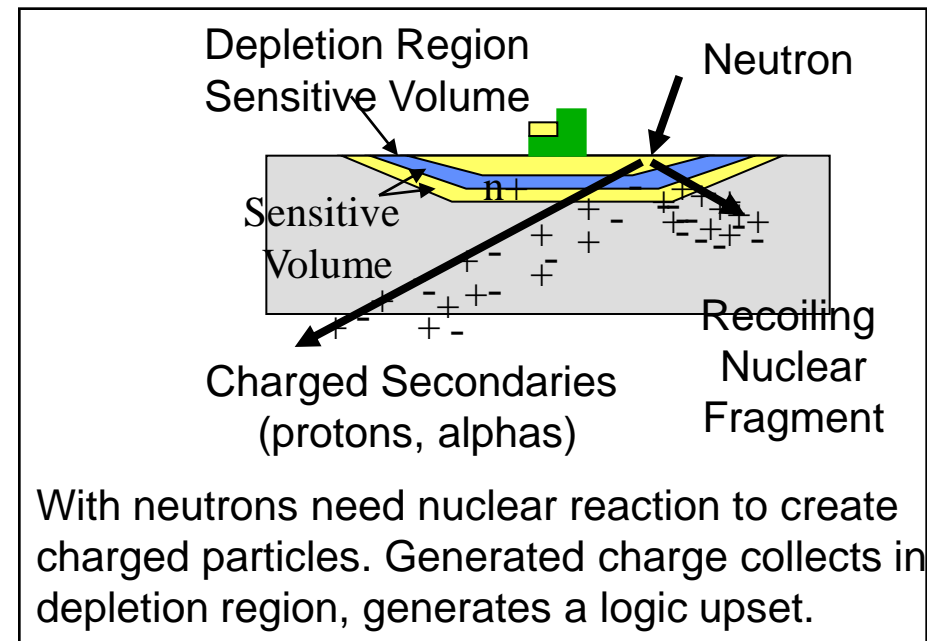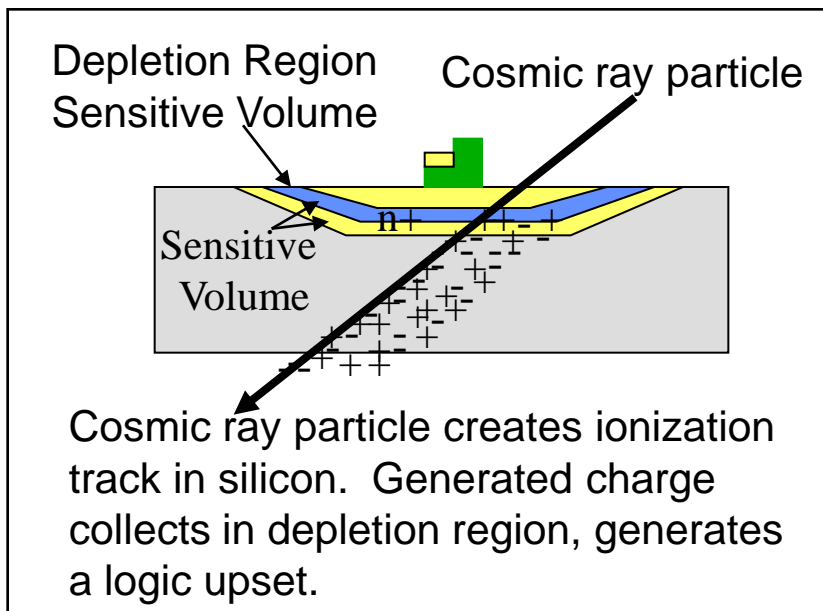
ATSB Transport Safety Report Aviation Occurrence Investigation AO-2008-70

- "The ATSB received expert advice that **the best way of determining if SEE could have produced the data-spike failure mode was to test the affected units at a test facility that could produce a broad spectrum of neutron energies**. However, the ADIRU manufacturer and aircraft manufacturer did not consider that such testing would be worthwhile for several reasons, including that:

- There were significant logistical difficulties in obtaining access to appropriate test facilities"

Neutron Single Event Effects (SEE) are faults in electronic devices caused by neutrons from cosmic rays

- **Neutrons are produced by cosmic rays in the upper atmosphere**

- **Neutrons have long mean-free paths so they penetrate to low altitudes**

- **Neutrons interact with Si and other elements in the device to produce charged particles**

- **Charged particles deposit charge in sensitive volume which cause state of node to change**

Depletion Region
Sensitive Volume   Cosmic ray particle

Sensitive
Volume

n

Cosmic ray particle creates ionization track in silicon. Generated charge collects in depletion region, generates a logic upset.

Depletion Region
Sensitive Volume   Neutron

Sensitive
Volume

n

Charged Secondaries
(protons, alphas)

Recoiling
Nuclear
Fragment

With neutrons need nuclear reaction to create charged particles. Generated charge collects in depletion region, generates a logic upset.
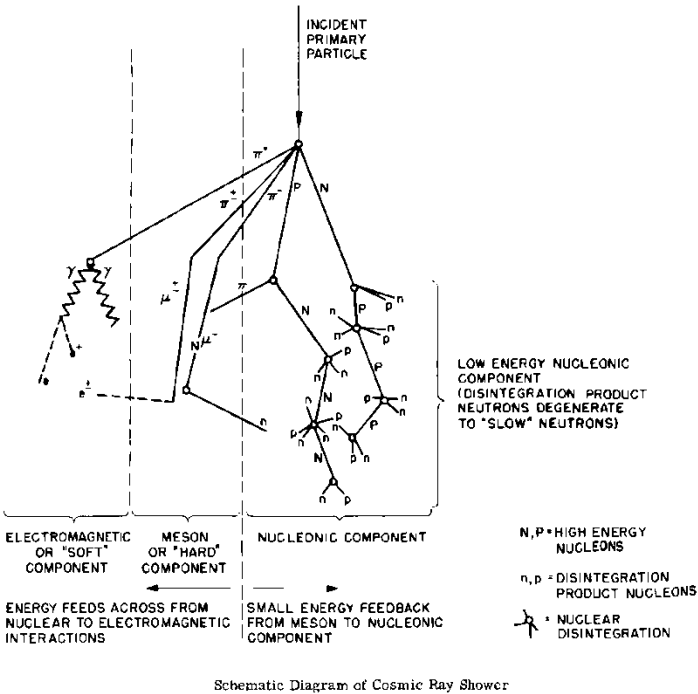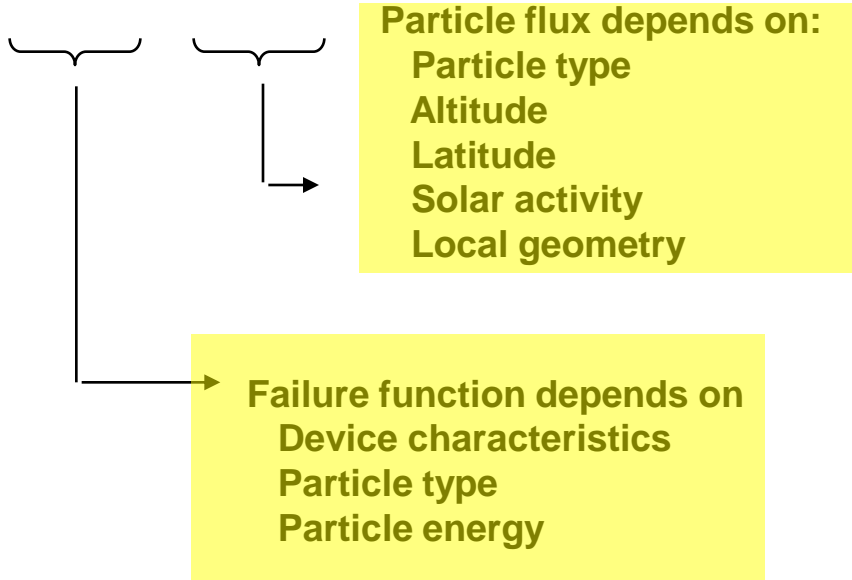
Los Alamos

Many types of single-event effects can cause failures

- **Soft errors**
  - Single event upset
  - Multiple event upset (a few % of SEU rate)
  - Silent data corruption

- **Hard errors**
  - Single event latchup
  - Single event burnup, gate rupture, etc.

- **High power devices**

- **First experiments were performed by the Boeing Co. for 777 certification**

- **Industry trends to lower voltages and smaller feature size are thought to increase the failure rate due to SEE**

- **Similar devices have very different failure rates**

- **The failure rate due to SEU is equal to all the other failure modes combined**

- **" Since chip SER is viewed by many as a legal liability (something that you know may fail) the public literature in this field is sparse and always makes management nervous". *SER History, Trends and Challenges* James Ziegler and Helmut Puchner**

Cosmic-ray induced failure rates

- **The failure rate due to cosmic-ray events is given by:**

$$F/t = \sum_p \int f_p(E_p) * \Phi_p(E_p) \ dE_p$$

Particle flux depends on:
Particle type
Altitude
Latitude
Solar activity
Local geometry

Failure function depends on
Device characteristics
Particle type
Particle energy

INCIDENT PRIMARY PARTICLE

LOW ENERGY NUCLEONIC COMPONENT (DISINTEGRATION PRODUCT NEUTRONS DEGENERATE TO "SLOW" NEUTRONS)

ELECTROMAGNETIC OR "SOFT" COMPONENT | MESON OR "HARD" COMPONENT | NUCLEONIC COMPONENT

N, P = HIGH ENERGY NUCLEONS

n, p = DISINTEGRATION PRODUCT NUCLEONS

* = NUCLEAR DISINTEGRATION

ENERGY FEEDS ACROSS FROM NUCLEAR TO ELECTROMAGNETIC INTERACTIONS | SMALL ENERGY FEEDBACK FROM MESON TO NUCLEONIC COMPONENT

Schematic Diagram of Cosmic Ray Shower

F/t is the number of fails / time

p is the particle type (neutron, protons, pions,…)
$f_p(E_p)$ is the number of fails /particle with energy E_p
$\Phi_p(E_p)$ is the number of particles/sec with energy E_p

The cosmic-ray neutron flux depends on altitude

- **Neutron flux at different altitudes can be obtained by**

$$I(A_1)/I(A_2) = \exp[(A_2 - A_1)/L]$$

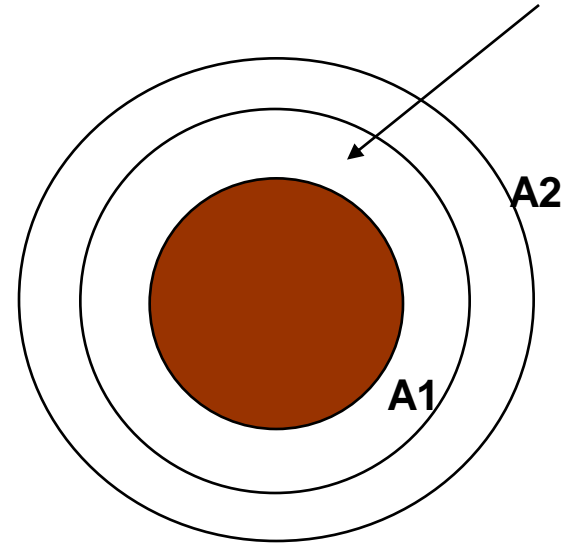**L is attenuation length of particle**
L ~ 136 cm^2/g for neutrons
L is different for other particles

A is the thickness of the air in g/cm^2

A(H) = 1033 - (0.3648H) + 4.26 \cdot 10^{-7}H^2 grams/cm^2
   H is the altitude above sea level in ft
   (Zeigler, IBM Journal of Research and Dev. _42_, 1998)

Thickness of air at sea level is 1033 g/cm^2 which is equivalent to over 4 feet of steel or 10 feet of concrete !!!

A2

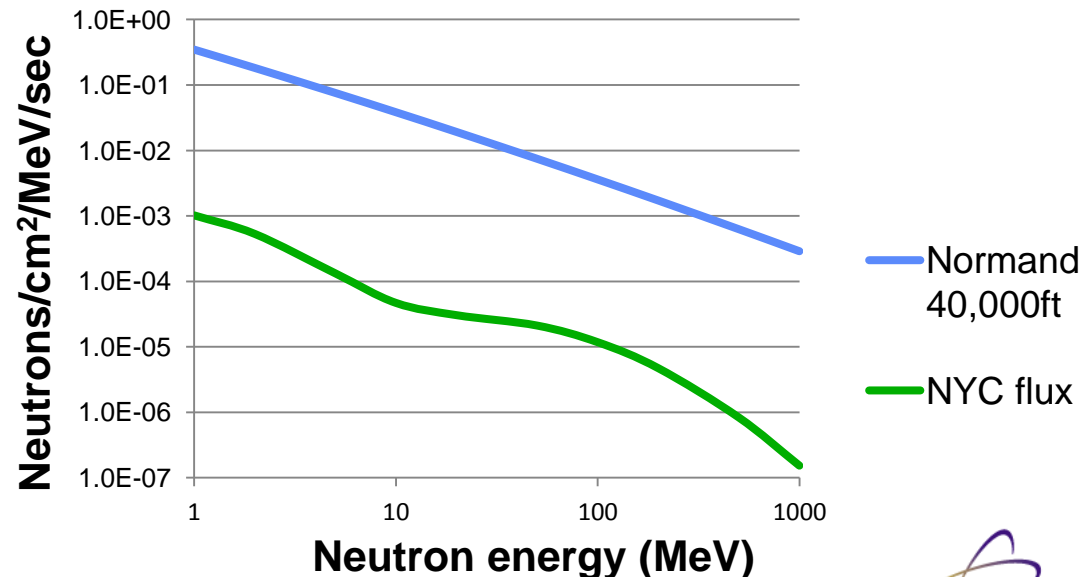A1

Energy dependence of cosmic-ray neutron flux

- **Neutron flux at 40,000 ft and 45^0 latitude (Normand, IEEE Trans. Nucl. Sci. 43 , 1996, 461)**

  $\Phi_n(E_n)$= 0.3459*$E_n^{-0.9219}$*exp[-0.01522$(Ln(E_n))^2$] n/cm²/sec/MeV

- **Neutron flux at NYC**

  $\Phi_n(E_n)$= 1.006e-6*exp(.35*$(Ln(E_n))$^2+2.1451*$Ln(E_n)$)

  +0.001011*exp(-0.4106*$(Ln(E_n))$^2-0.667*$Ln(E_n)$) n/cm²/sec/MeV

E_n is neutron energy in MeV

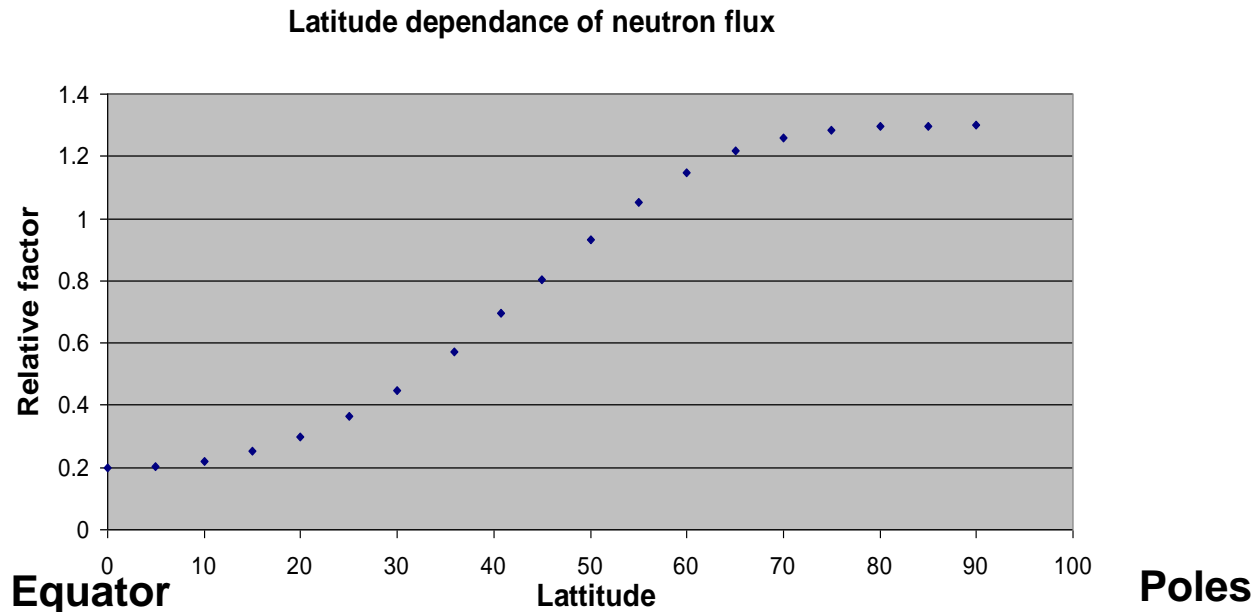# Cosmic-ray neutron flux depends on latitude

- **The cosmic ray neutron flux depends on the latitude and is parameterized by the following expressions:**

  $F(L)=0.6252*\exp[-0.461\cos^2(2L)-0.94\cos(2L)+0.252]$

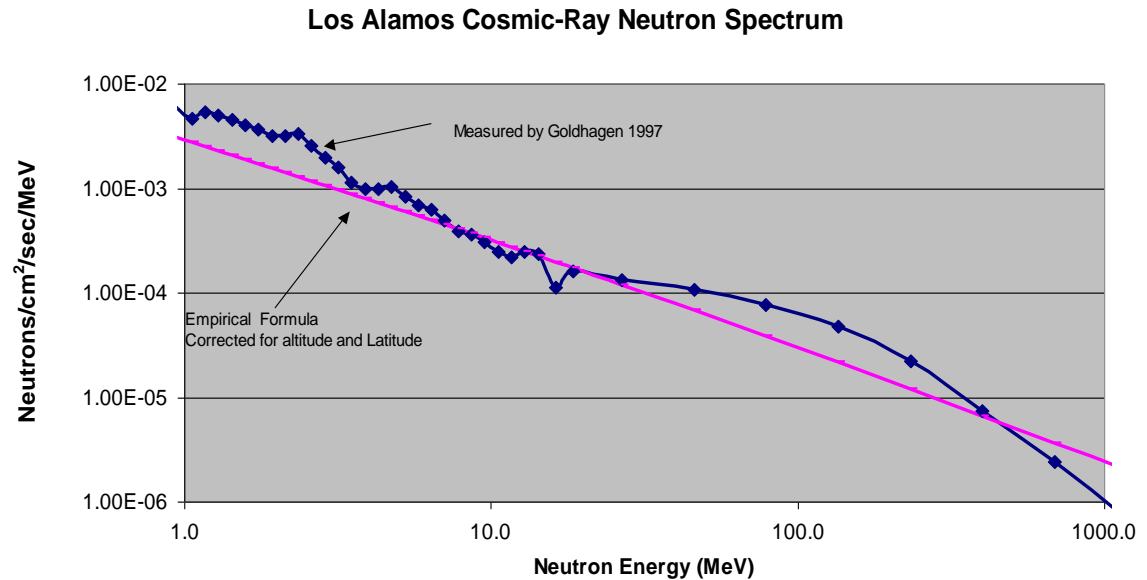 **(Normand, IEEE Trans. Nucl. Sci 43, 1996, 461)**

  L is the latitude in degrees

- **Shape changes with latitude**

Latitude dependance of neutron flux

Equator   Lattitude   Poles

Measured cosmic ray flux agrees with formulas at 7000 ft at Los Alamos

- **The neutron flux was measured by Goldhagen et al. (1997) using Bonner spheres**

Los Alamos Cosmic-Ray Neutron Spectrum

Y-axis: Neutrons/cm²/sec/MeV (1.00E-02 to 1.00E-06)

X-axis: Neutron Energy (MeV) (1.0 to 1000.0)

Measured by Goldhagen 1997

Empirical Formula
Corrected for altitude and Latitude

Integrated cosmic-ray neutron flux above 10 MeV (neutrons/cm²/sec)

	n/cm2/s	Relative
Sea level (New York City)	0.00565	1
7000 ft (Los Alamos)	0.019	3.4
40,000 feet	1.53	270

NNSA

Los Alamos

When neutrons interact with Si many charged particles are produced

- **Neutrons strike silicon and produce recoil Silicon nuclei and alpha particles, etc.**

Incident neutron energy (MeV)	Max recoil energy (MeV)	Range of particle in Si (μm)	Energy loss (keV/μm)
30	6 (Si)	3.6	2750
100	14 (Si)	6.2	3300
50	40 (α)	710	32

- Simple models exist to estimate upset rates based on recoil spectra

Chadwick and Normand
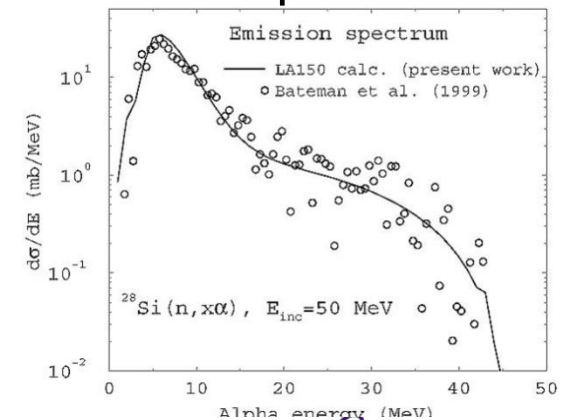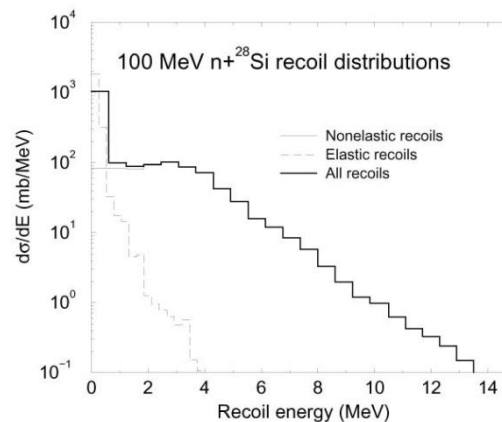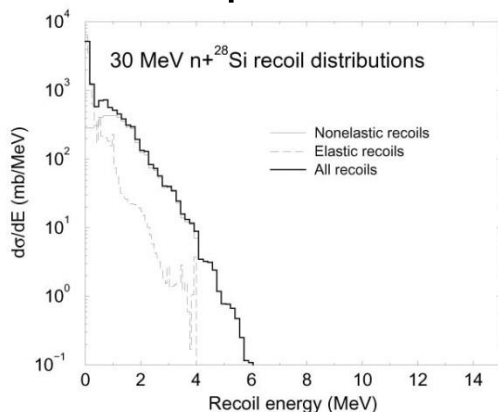
# Accelerated testing is essential

- **Design criteria for servers (100 GB memory) is 1 fail / year from SEU**
  - If need to know the failure rate to 10%, need 100 fails
  - Need to run server for 100 years! RAMs change every 18 months
- **Need to perform accelerated testing with acceleration rate~ 5000 (3.6×10^4) to get answer in 1 week (1 day) if testing entire server**
- **Need to test individual chips before they go into system**
  - A 100GB server may have ~300 memory chips
  - The failure rate of a single chip is 1 fail / 300 years
- **This requires an acceleration factor of ~ 10^7 for 1 day of testing to get 100 fails**

Los Alamos Neutron Science Center (LANSCE)

Weapons Neutron Research High-energy Neutrons

800 MeV Linac 1 km long Pulsed

Isotope Production Facility

Lujan Center Low-energy neutrons
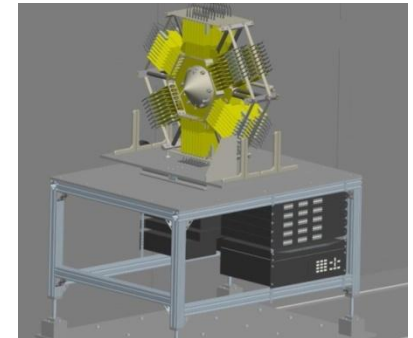
Proton Radiography
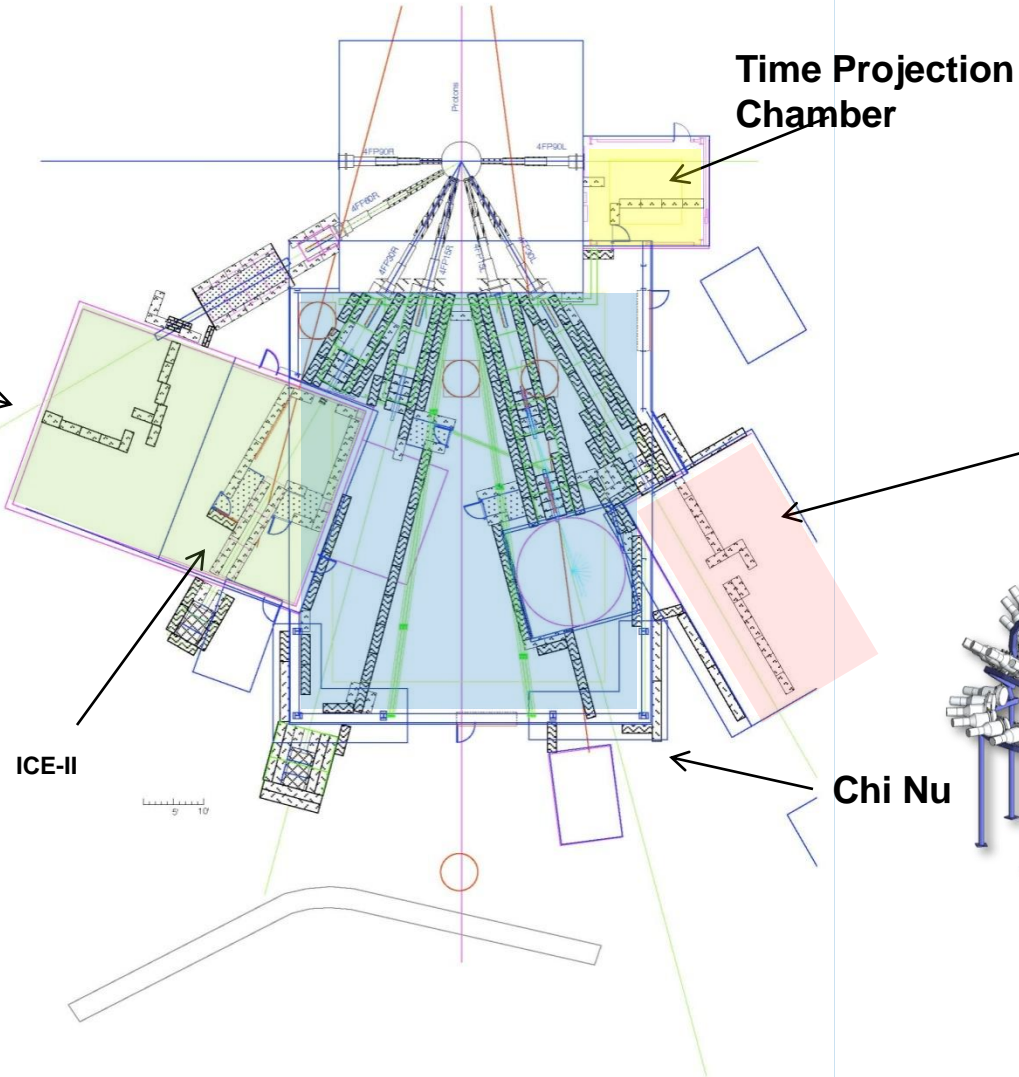
Ultra Cold Neutrons

The high-energy neutron spallation source at LANSCE

- **5 μA (1 KW in target) of proton current for high-energy neutron production (Target-4)**
  - Neutrons are produced via spallation reactions with tungsten target
  - Tungsten target is 7.5 cm long and 3 cm diam no moderation
  - Target is located inside a 2 m diam vacuum chamber
  - Massive shielding around target
  - Six flight paths operate simultaneously
- **Neutron Single Event Effect flight path and test area. Second area developed in 2012**
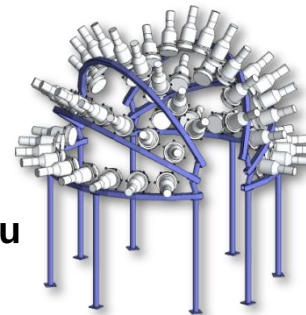

WNR Neutron Flux

Legend: 15 Deg, 30 Deg, 60 Deg, 90 Deg

E_n (MeV) — Y (n/p/MeV/Sr)
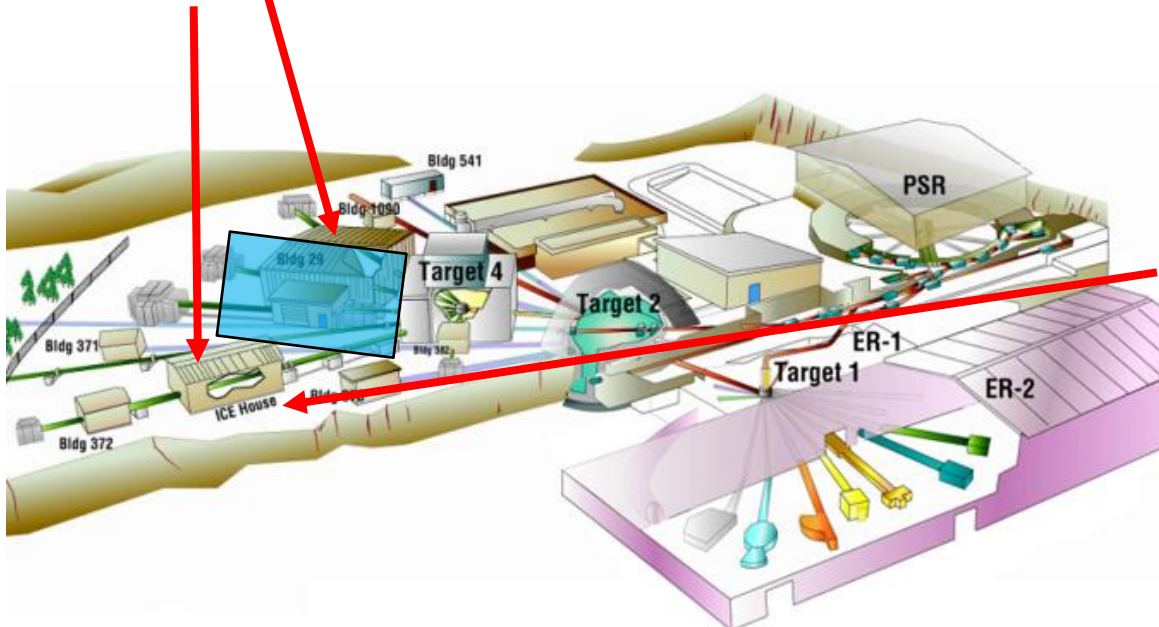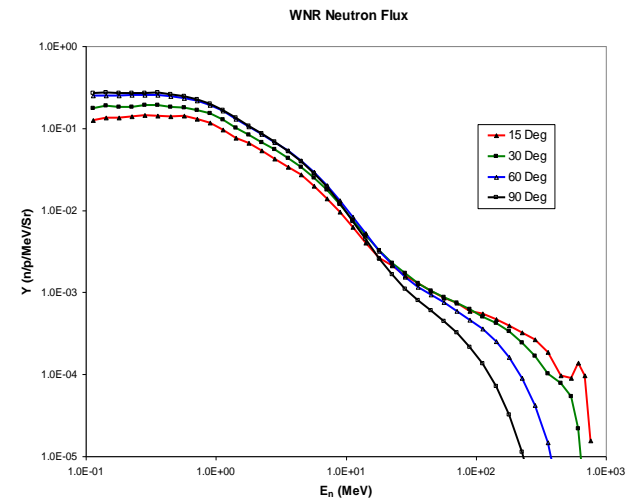
High-energy neutron flight paths at LANSCE/WNR

GEANIE

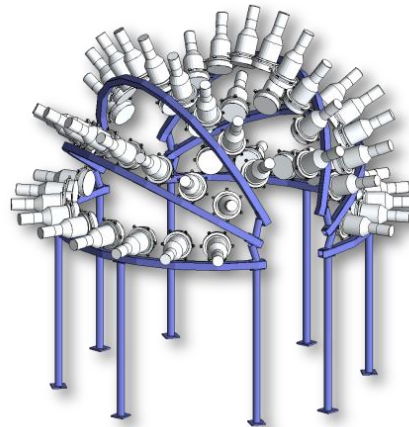Time Projection Chamber

ICE House

ICE-II

Chi Nu

Los Alamos

Many instruments have been developed for nuclear science measurements at LANSCE

GEANIE (n,xγ)

Chi Nu (n,xn+γ)

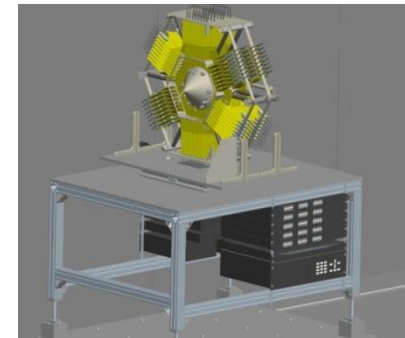**DANCE (n,γ)**
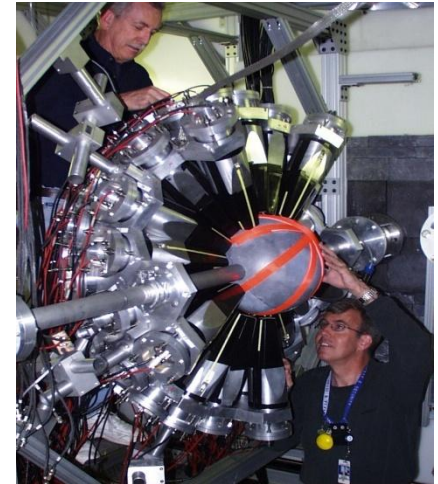
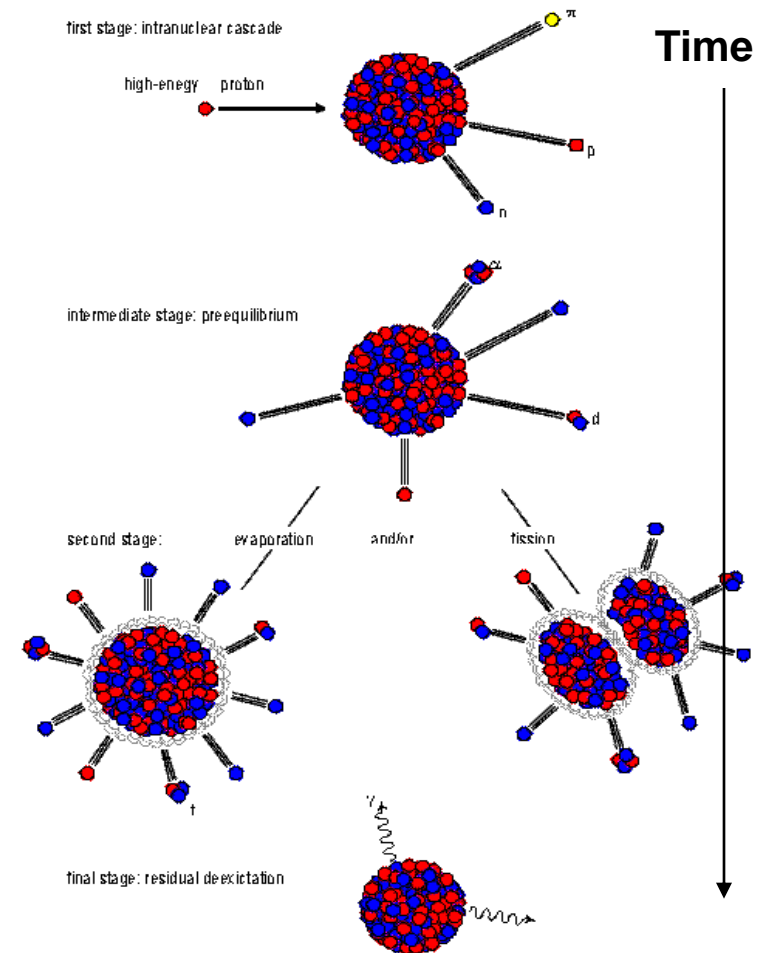**SPIDER**
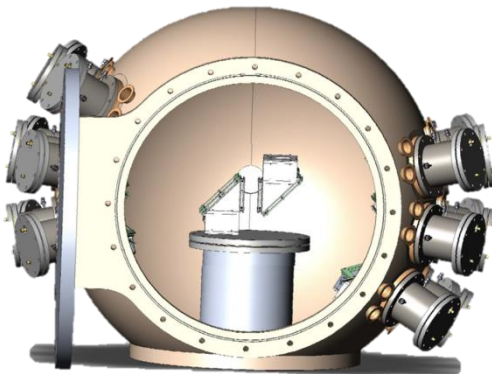
Fission

LSDS

TPC

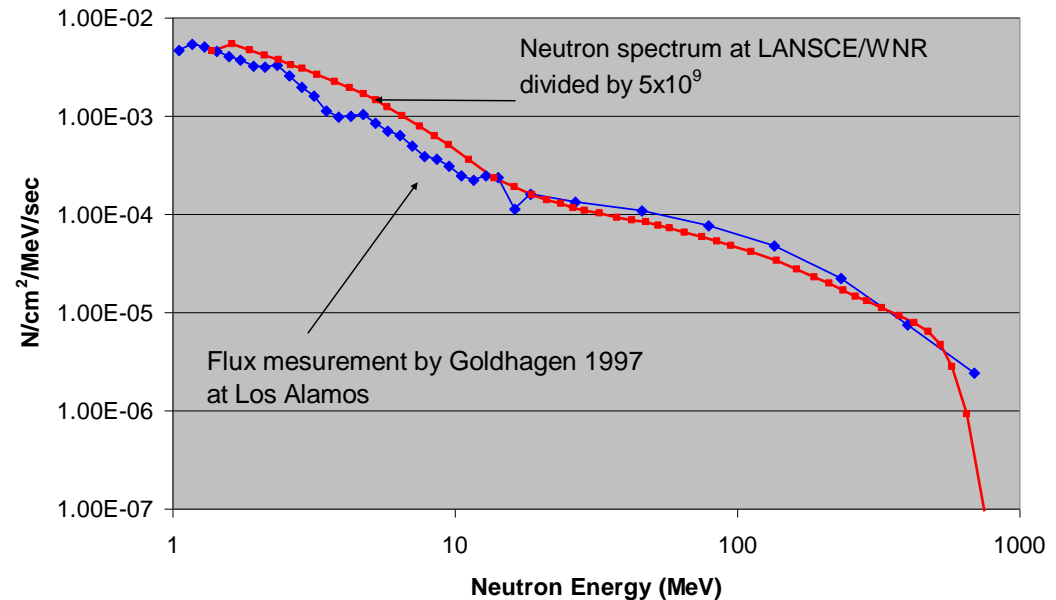# Neutrons at LANSCE are produced by spallation reactions

- **Difficult to produce high-energy neutrons. No charge- can't accelerate**

- **Spallation reactions occur when high energy particles strike a high z target. Spallation reactions produce a wide range of output particles**

- **In the first stage of the reactions, high-energy nucleons are produced**

- **At later times, the nucleus "thermalizes" and lower energy neutrons and nuclei are produced**

- **Charged particles are removed from the neutron beam by magnets**

Time

first stage: intranuclear cascade

high-enegy proton

intermediate stage: preequilibrium

second stage: evaporation and/or fission

final stage: residual deexictation

The high-energy spallation neutron sources provide excellent capability for SEE testing and measuring

- **Because neutrons are produced by spallation by the same basic process as in the atmosphere, the neutron spectrum can be similar to the neutron spectrum produced by cosmic rays in the atmosphere**

- **Neutron spectrum determined precisely by time-of-flight techniques**

Neutron Flux at Los Alamos and LANSCE/WNR

Y-axis: $N/cm^2/MeV/sec$ — values from 1.00E-07 to 1.00E-02

X-axis: Neutron Energy (MeV) — 1 to 1000

Neutron spectrum at LANSCE/WNR divided by 5×10^9

Flux mesurement by Goldhagen 1997 at Los Alamos

- **Accelerated soft error rate (SER) testing is the preferred method to determine failure rates (JESD89)**

    - **LANSCE beam intensity is approximately 10^6-10^8 times greater than the flux at aircraft altitudes or sea level. One hour of testing is equivalent to over 100 years of testing at aircraft altitudes.**

    - **Direct and accelerated SER measurement are more reliable than projections from mono-energetic sources**

    - **Devices may be placed in the beam in air and operated under normal conditions.**
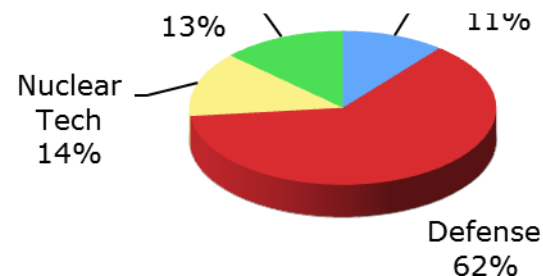
Nuclear Science User Program statistics for 2013 run cycle
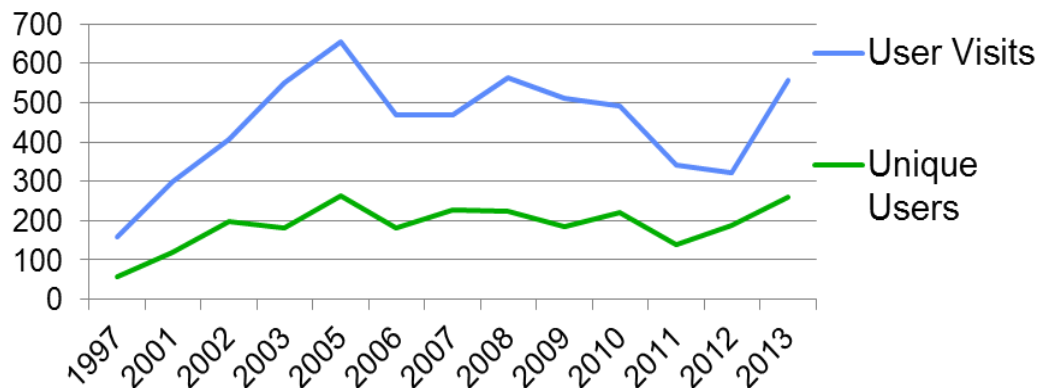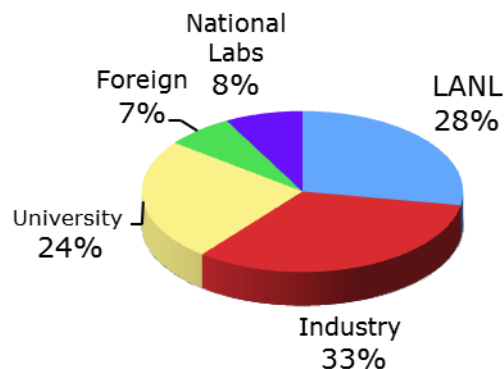
Several neutron sources provide testing capabilities

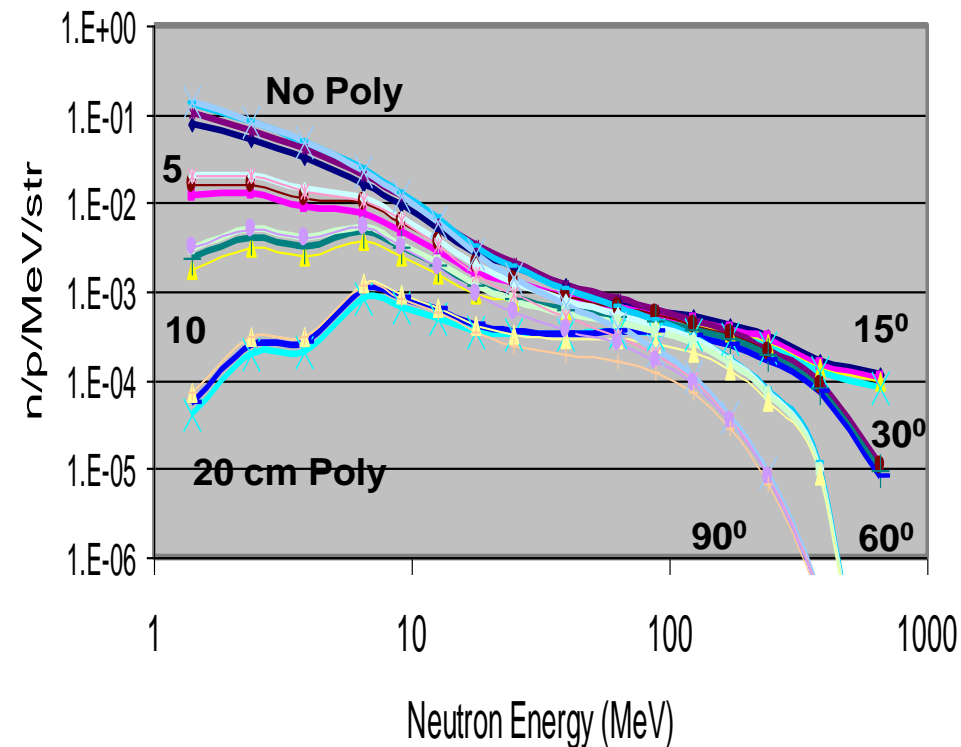| Facility	LANSCE	TRIUMF	TRIUMF	TSL
Location	USA	Canada	Canada	Sweden
Beam energy	800	400	116	180
Neutrons/cm^2/s	5×10^5/ 1.2×10^6	3×10^6	5×10^4	10^6
Spot size (cm)	2.5,5,8	5X12	20X100	1-30
Operation (hrs/year)	3000*2	3000	800	9 mo

Notes:

1. Research Center Nuclear Physics at Osaka Japan also does semiconductor testing
2. TSL facility is uncertain beyond 2015
3. CHIPIR facility at ISIS (~10^6 n/cm^2/s) begin operation 3/2014
4. Two flight path at LANSCE for testing . New flight path has twice flux as old Flight Path
5. LANSCE neutron intensity will increase X2.5 in 2014

The LANSCE neutron spectrum is similar to the atmospheric neutron spectrum produced by cosmic rays

**Neutron Flux at Los Alamos and LANSCE/WNR**

Neutron spectrum at LANSCE/WNR divided by 5×10^9

Flux mesurement by Goldhagen 1997 at Los Alamos

y-axis: N/cm^2/MeV/sec

x-axis: Neutron Energy (MeV)
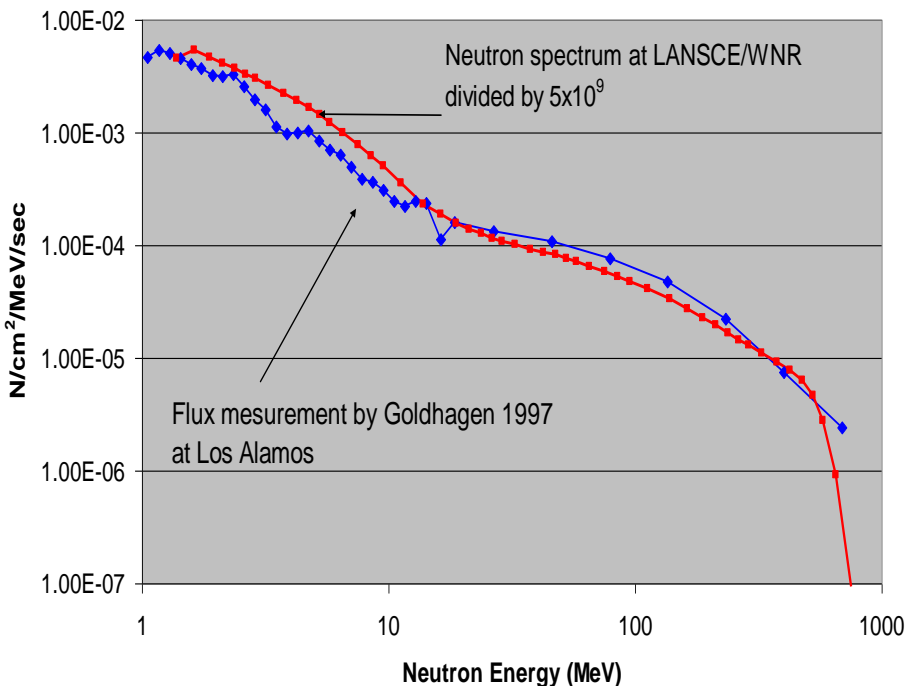
Neutron spectra for various flight paths and absorbers

No Poly

5

10

20 cm Poly

15⁰

30⁰

90⁰

60⁰

y-axis: n/p/MeV/str

x-axis: Neutron Energy (MeV)

- **The 30-degree flight path with no absorbers provides the best match for the cosmic-ray neutron spectrum**

Neutron energies are determined by Time-of-Flight
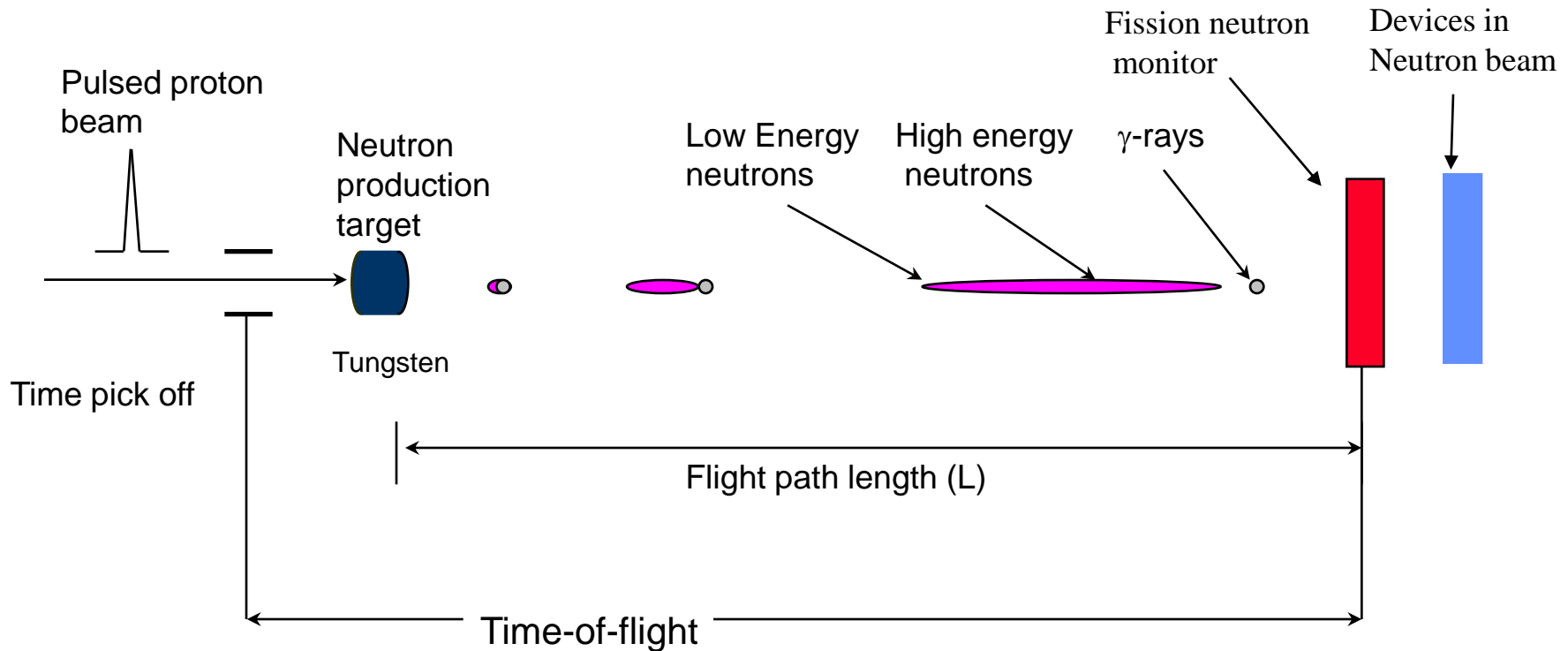
Neutron TOF = $\dfrac{72.3\,L}{\sqrt{E_n}}$ (non-relativistic)

γ-ray TOF = $\dfrac{L}{c}$ c is velocity of light

Example: L= 20m E_n= 1 MeV E_n = 100 MeV
                    TOF_n= 1.5 μs TOF_n= 150 ns
                    TOF_γ = 67 ns

LANSCE proton beam parameters

- **Time structure**
  - Macropulses
    - » ~625ms wide
    - » 100 macropulses/s presently 40 MP / sec
  - μpulses
    - » Within each macropulse are μpulses. μpulses are separated by integral multiples of 180 ns. Typically μpulse separation is 1.8 μs
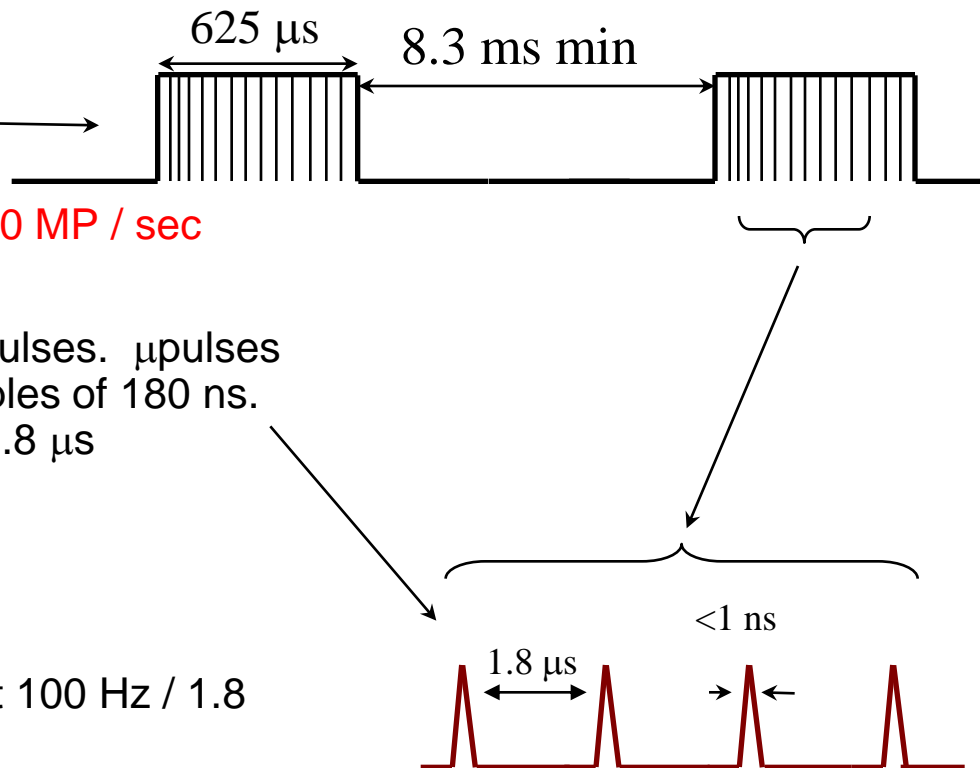   - » Width of μpulse is < 1 ns
- **Intensity**
  - Approximately 5×10^8 protons/μpulse
  - Approximately 35,000 μpulses/s (at 100 Hz / 1.8 μsec spacing)
  - Average proton beam current is 5 μA (at 100 Hz)
  - Approximately 30 neutrons(E_n>1 MeV) /μp/cm^2

625 μs   8.3 ms min

<1 ns

1.8 μs

Neutron flux is monitored using a fission ionization chamber

- **Neutron monitor measures the shape and magnitude of the neutron spectrum**

- **Neutron monitor is "thin" so it does not perturb the beam**

- **Neutron monitor provides a signal to the experimenters which is proportional to the number of neutrons in the test—"fission pulse"**

- **Time of event is determined to ~ 1 nsec enabling precise neutron spectrum measurements**

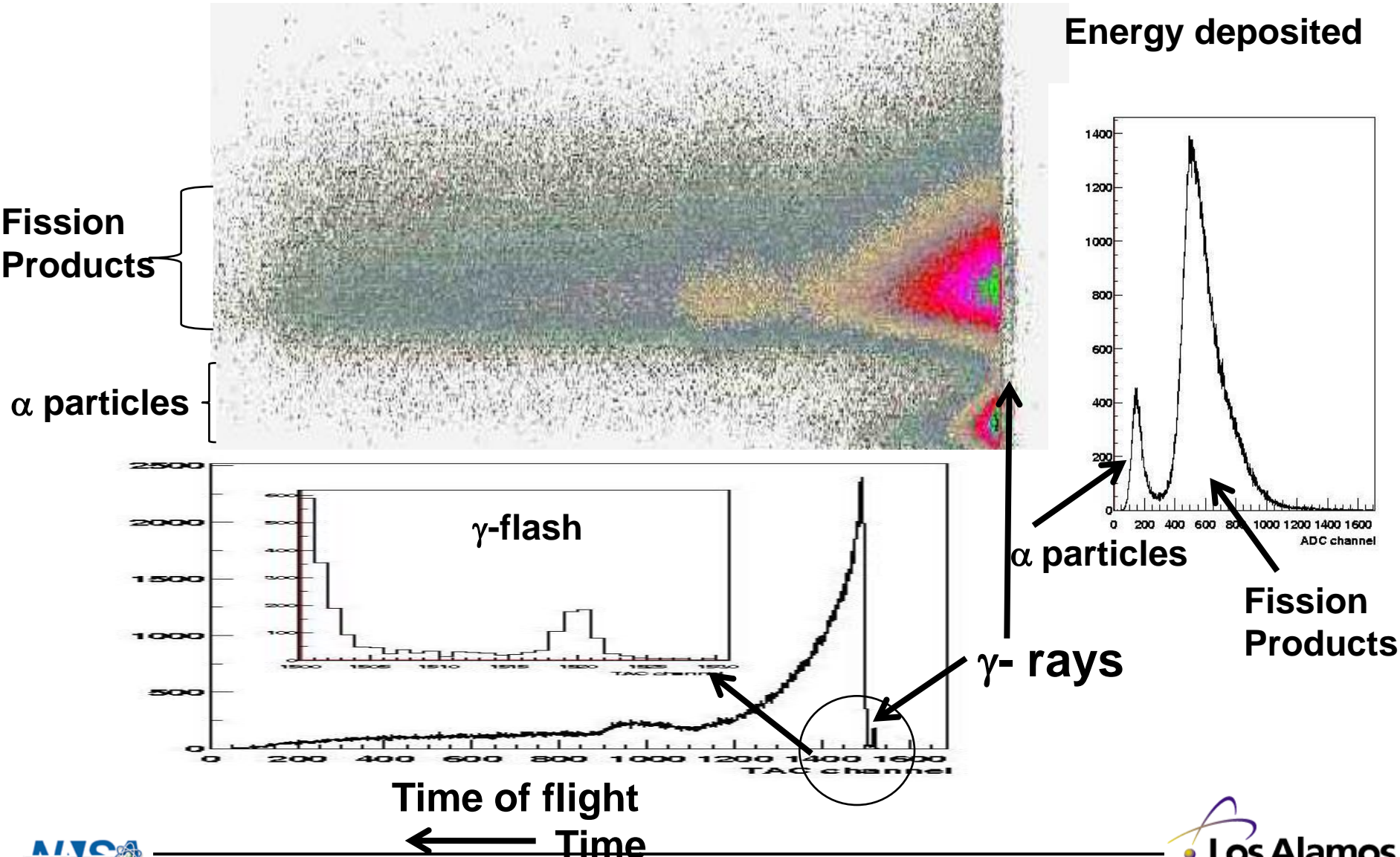- **Need to eliminate other particles are which detected (alpha particles)**

Fission chamber
Is filled with gas

+ V

Neutron beam

Fission Products and alpha particles

^{238}U fission deposit

Output pulse
To signal processing electronics

"fission pulse"
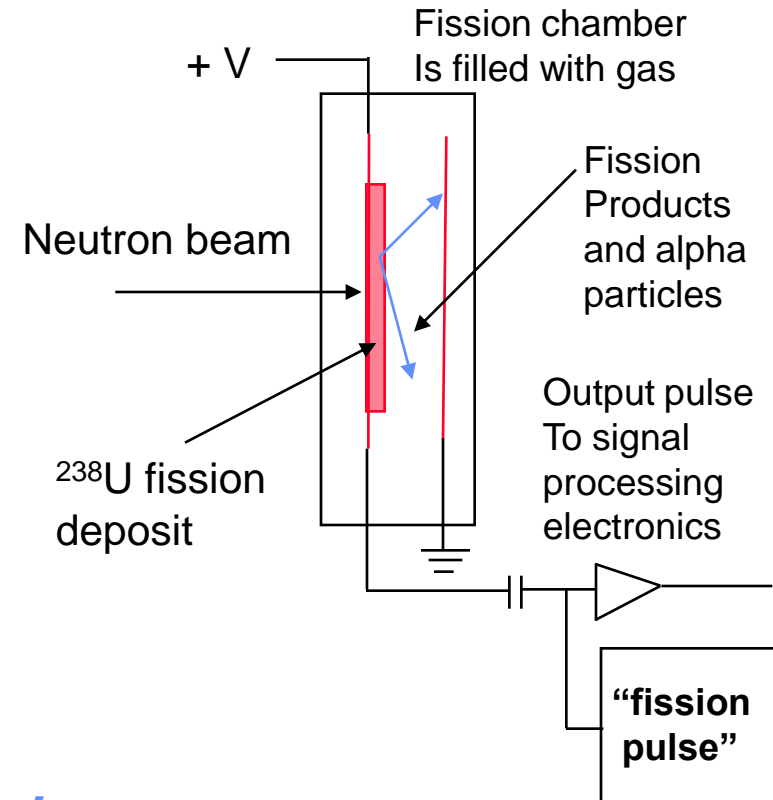
# of neutrons / sec / MeV =

[Number of fission events /sec]/[fission cross section]/[thickness of fission foil]

Known from other measurements

Recorded in the measurement

Output from fission chamber measurement is the numbers of neutrons that pass through fission foil. This gives the number of neutrons/cm2 per "fission pulse".

Measuring fission in 2-D removes α-particle background

Energy deposited

Fission Products

α particles

γ-flash

α particles

Fission Products

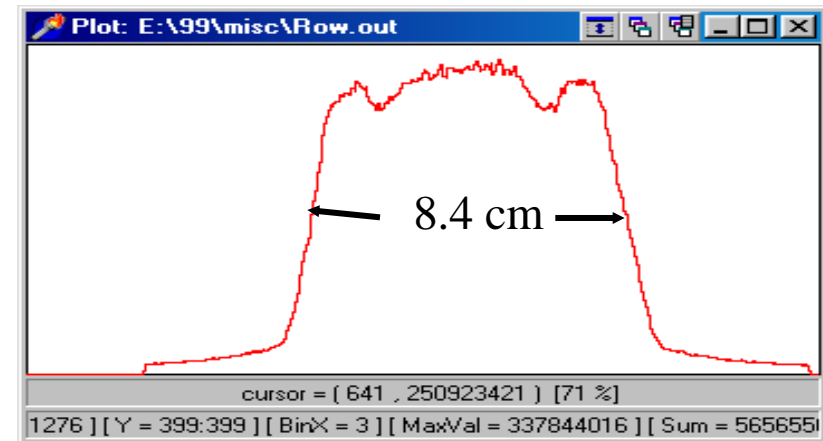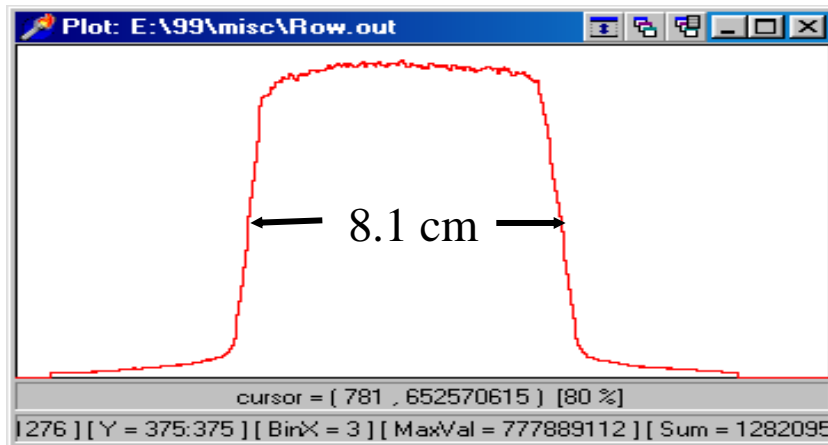**γ- rays**
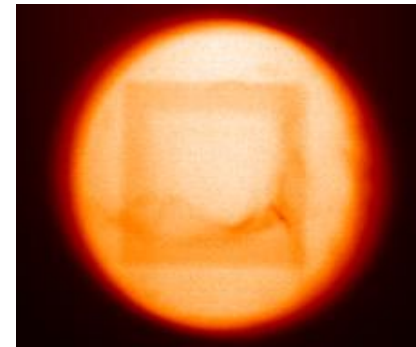
Time of flight

Time

An image plate of the beam spot shows uniform exposure

- **Neutron beam spot size is determined by steel collimation (~ 3 feet long)**

Upstream

Downstream

8.1 cm

8.4 cm

Neutrons can cause failures in high-power semiconductor devices

- **IGBT are semiconductor devices that are used in many high-power applications such as BART, hybrid cars, accelerator RF systems, etc.**

- **The lifetime of these devices in neutron fields depends on the electric field or the applied voltages**

- **Tests show a dramatic decrease in lifetime at a critical voltage which is significantly below the rated operating voltage**

IGBT DATA SUMMARY
3300 V Devices

Beam Lifetime (minutes) vs. C/E Voltage (Volts)

Rated Voltage
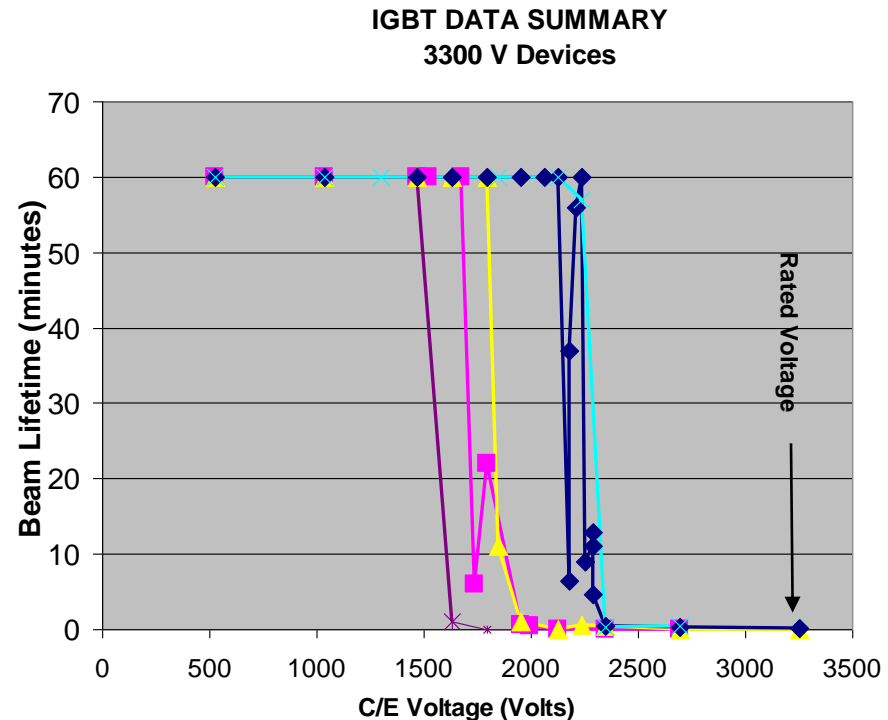
One neutron can stop a train

Results of LANSCE/WNR measurements determine problem with ASCI Q-Machine

- The ASCI Q-Machine has 2048 nodes with a total of 8192 processors.

- During commissioning, it was observed that the Q-machine had a larger than expected failure rate. Approximately 20 fails / week (~3 fails / day).

- The question was whether this could be the result of neutron single-event upset.


ASCI Q-Machine at Los Alamos National Laboratory

Fails/day ~ [# of fails/neutron] * [# neutrons/day]

Measured at LANSCE

Cosmic-ray neutron flux

The neutron environment and the system response was measured

- The neutron intensity was measured in the Q-Machine room. The values obtained agreed with the Goldhagen values

- The system response was measured by putting one module of the Q-Machine in the LANSCE/WNR beam.

- Results of measurement accounted for approximately 80% of the failures. (IEEE Trans. Dev. Mat. Reliab. 5 2005)

- The failures were traced to a cache memory that was not error corrected.

- This result may have significant impact on future large computer systems
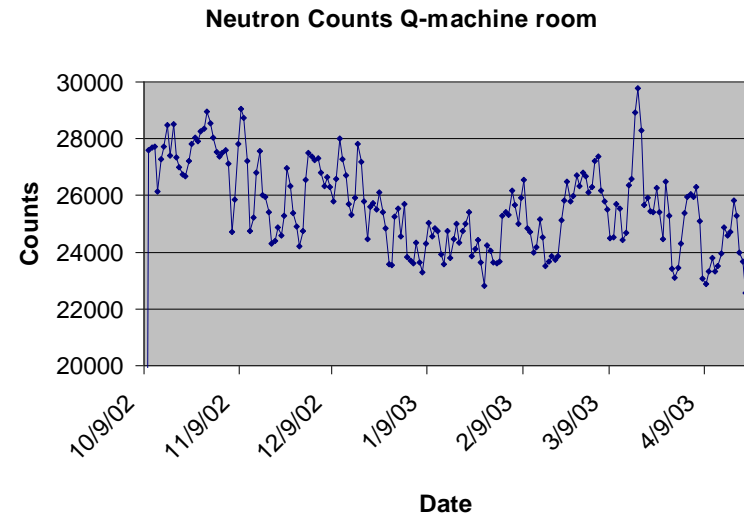
One neutron can stop a calculation

Santa Fe New Mexican February 2004
"..Q's weakness is the result of…cosmic ray bombardment…a microprocessor that doesn't have a backup system .."

Neutron Counts Q-machine room

**Date**

Issues for semiconductor testing

- Development of standards and specifications so customers can know what the failure rate is in the chips they purchase. Joint Electron Device Engineering Council (JEDEC) Standard JESD89.

- Knowledge of neutron flux in the environment of semiconductor devices is necessary. This includes the effects of packaging, geometry, orientation of devices, proximity of other objects, etc. MC modeling

- Precise measurement of neutron fluxes in testing laboratories so different tests can be compared

- Good, validated models, including nuclear data, that predict failures are need to be developed and improved.

- Measurement of neutron energy dependent failure rate for various devices $f_n(E_n)$ # of fails / neutron as function of neutron energy
    - "Monoenergetic" neutron sources
    - Spectrum unfolding
    - Time of flight

- Calibration of accelerated testing predictions with environmental testing.

Summary

- **Single Event Effects are a very significant failure mode in modern semiconductor devices that may limit their reliability**

- **Accelerated testing is important for semiconductor industry**

- **Considerable more work is needed in this field to mitigate the problem**

- **Mitigation of this problem will probably come from Nuclear Scientists and Electrical Engineers working together**
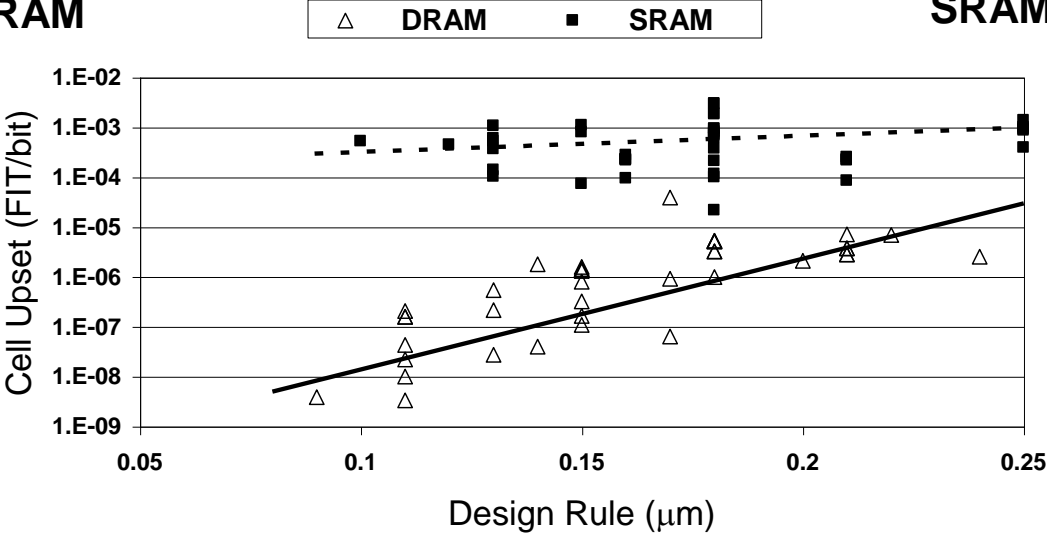
End of talk

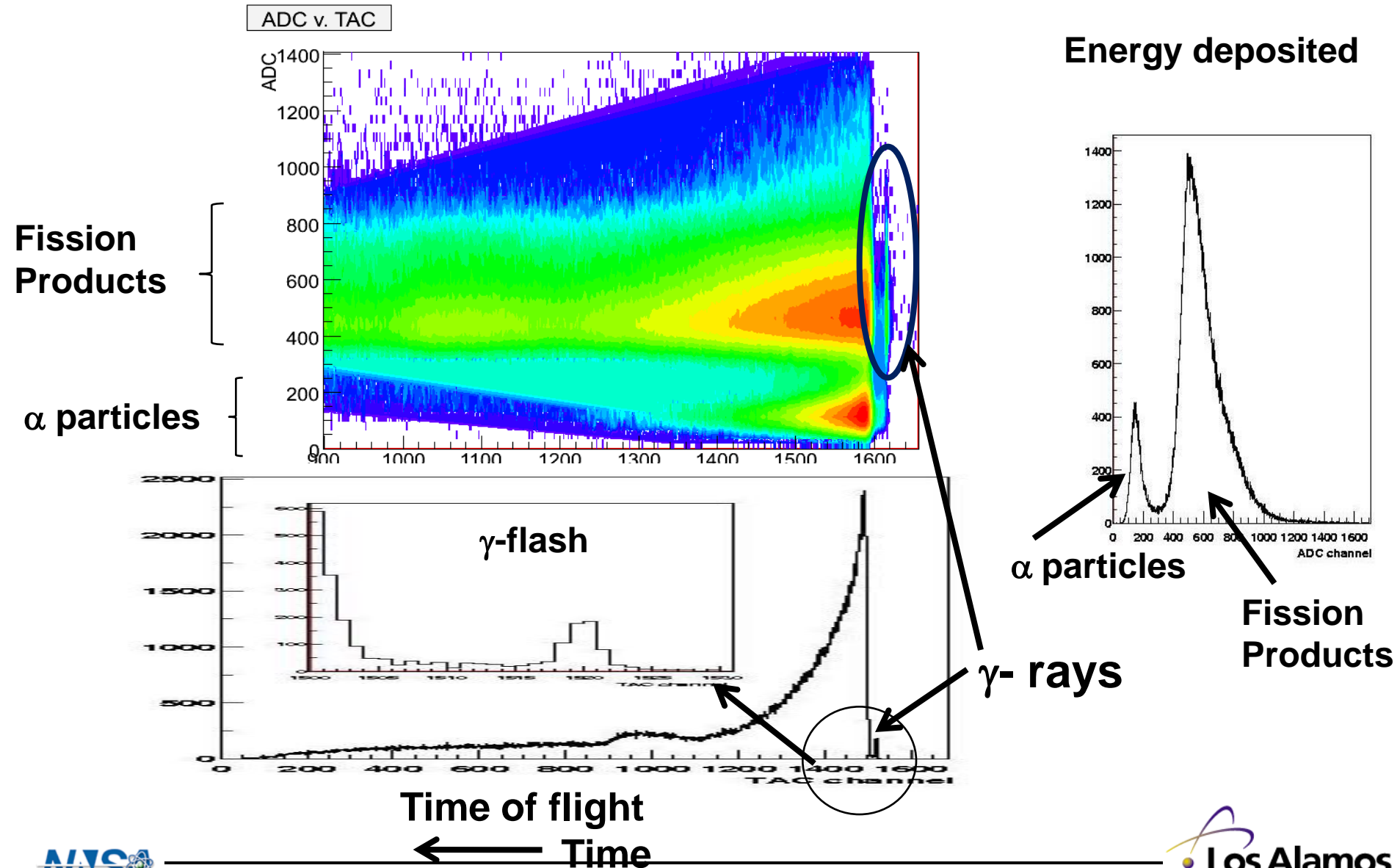# SRAM and DRAM upset rates depend on feature size
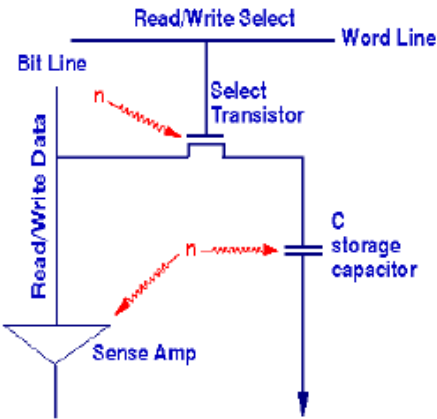
DRAM

△ DRAM ■ SRAM
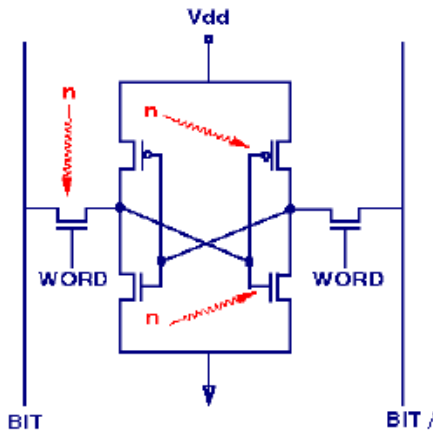
SRAM

A FIT or Failure-in-Time is the number of failures in 10^9 hours of operation
At 1 FIT a 1GB memory will fail once an hour

Measuring fission in 2-D removes α-particle background

ADC v. TAC

Energy deposited

Fission Products

α particles

γ-flash

Time of flight

Time

γ- rays

α particles

Fission Products

Issues for industry users

- **Easy access to facility**
  - Simple agreements
  - Scheduling
  - Approval process for users
  - Inexpensive to use
  - Easy to travel to facility
  - Internet available

- **Easy set up of experiments**
  - Simple delivery of user equipment
  - Simple shipping to and from facility
  - Easy release of activated equipment
  - Ability to handle activated samples

- **Experiment operation**
  - Reliable accelerator operation
  - Accurate measurement of neutron flux
  - Neutron flux information can be part of their data stream
  - Easy to change beam spot size
  - Easy to connect and set up their equipment

- **Other**
  - Good restaurants and accommodations

The cosmic-ray neutron flux depends on altitude

- **Neutron flux at different altitudes can be obtained by**

  $$I(A_1)/I(A_2)= \exp[(A_2-A_1)/L]$$

    - L is attenuation length of particle
    - L~ 136 cm^2/g for neutrons
    - L is different for other particles

- **A is the thickness of the air in g/cm^2**

- **A(H) = 1033-(0.03648H)+4.2610^{-7}H^2 grams/cm^2**

    - H is the altitude above sea level in ft (Zeigler, IBM Journal of Research and Dev. <u>42</u>, 1998)

- **Thickness of air at sea level is 1033 g/cm^2 which is equivalent to over 4 feet of steel or 10 feet of concrete !!!**